"It's full of asteroids!": Solar system science with a large field of view

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Thematic area: Planetary Systems

Solar system science with astrophysics assets

There is a long history of solar system observations with space-based astrophysics assets, from the Infrared Astronomical Satellite (IRAS) in the 1980s to present-day facilities such as the Hubble Space Telescope. Some astrophysics assets include a prominent solar system component as part of the original mission plan (e.g., WISE), some include this component late in mission design or even after primary operations begin (e.g., HST), and others never intended to support solar system observations until the proper opportunity arose (e.g., Kepler, Chandra). Nevertheless, the solar system community finds a way to make use of these facilities for ground-breaking science. The time allocation, determined by peer-review, for solar system observations is typically not that high, yet they make a disproportionately large impact. According to Holler et al. (2018), 2.3% of HST orbits between 2014 and 2017 were devoted to solar system observations, while 15.4% of the press releases in that time span were related to these projects. Solar system science has proven to be a powerful tool for generating interest in space telescopes among the general public and will continue to do so for next-generation facilities.

These next-generation facilities, regardless of what form they take, will have larger apertures, larger fields of view, and more sensitive instrumentation than their predecessors. The prospects for solar system science with these facilities are substantial, particularly in the area of space-based surveys for the detection of minor bodies. In the past decade alone there have been numerous advances in the study of minor bodies, including the first detections of objects in previously uncharacterized populations. Such ground-breaking discoveries include the first Earth Trojan asteroid (Connors et al., 2011), the first interstellar asteroid (Meech et al., 2017), and the first object orbiting beyond 100 AU (Sheppard et al., 2018). As of early 2019, these particular objects remain the only known members of their respective populations, each of which can provide valuable information about the formation and evolution of planetary systems. An especially interesting aspect of Earth Trojans is their potential for future manned spaceflight missions due to their proximity to Earth. As discussed in Holler et al. (2018), the Wide Field InfraRed Survey Telescope (WFIRST) has a field of regard (range of solar elongation angles available to the telescope) that reaches angles as small as 54°, and thus would be capable of carrying out a survey for additional Earth Trojans. In general, a future space-based survey mission, ideally with a large field of view and deep-imaging capabilities, would provide the means to discover more objects in these new and intriguing populations.

Targeted solar system surveys are not necessarily required to make advances in minor body science. Surveys focused on astrophysical targets such as exoplanets, supernovae, and galaxies, can provide the coverage and depth needed to identify and characterize foreground minor bodies. One particularly powerful example is the potential for astrophysics surveys to contribute to the completion of a congressional mandate to detect 90% of all near-Earth asteroids (NEAs) larger than 140 meters in diameter, as per the NASA Authorization Act of 2005[1]. A full inventory of these objects is important for planetary protection, as NEAs are the most likely small bodies to be potentially hazardous to life on Earth. The WISE and NEOWISE missions made significant progress in this regard, but the majority of this inventory remains incomplete. The NEOCam mission was proposed to continue this effort, but it remains unfunded to-date. Other avenues must therefore be pursued, including serendipitous detection of NEAs in astrophysical survey fields. As shown in Figure 1, hundreds of minor bodies, including NEAs, main belt asteroids (MBAs), and Kuiper Belt Objects (KBOs), are present in each square degree near the ecliptic. A mission with a sufficiently large field of view and deep imaging capabilities would be best able to take

[1] https://www.govinfo.gov/content/pkg/PLAW-109publ155/pdf/PLAW-109publ155.pdf

advantage of this high target density.

The prospects for serendipitous detection of minor bodies is highly dependent on mission and survey parameters. Thus, for the remainder of this white paper, we will discuss the prospects for two hypothetical targeted surveys that require a space-based facility with deep imaging capabilities (i.e., sensitive instrumentation and wide-band filters) and a wide field of view (>0.2 deg^2). These two surveys would deliver high-impact minor body science by moving the inventory of irregular satellites (captured minor bodies) around the giant planets closer to completion and expanding on the number of known Inner Oort Cloud objects beyond 100 AU. Each of these populations contributes a different piece to the puzzle of the early dynamical evolution of our solar system.

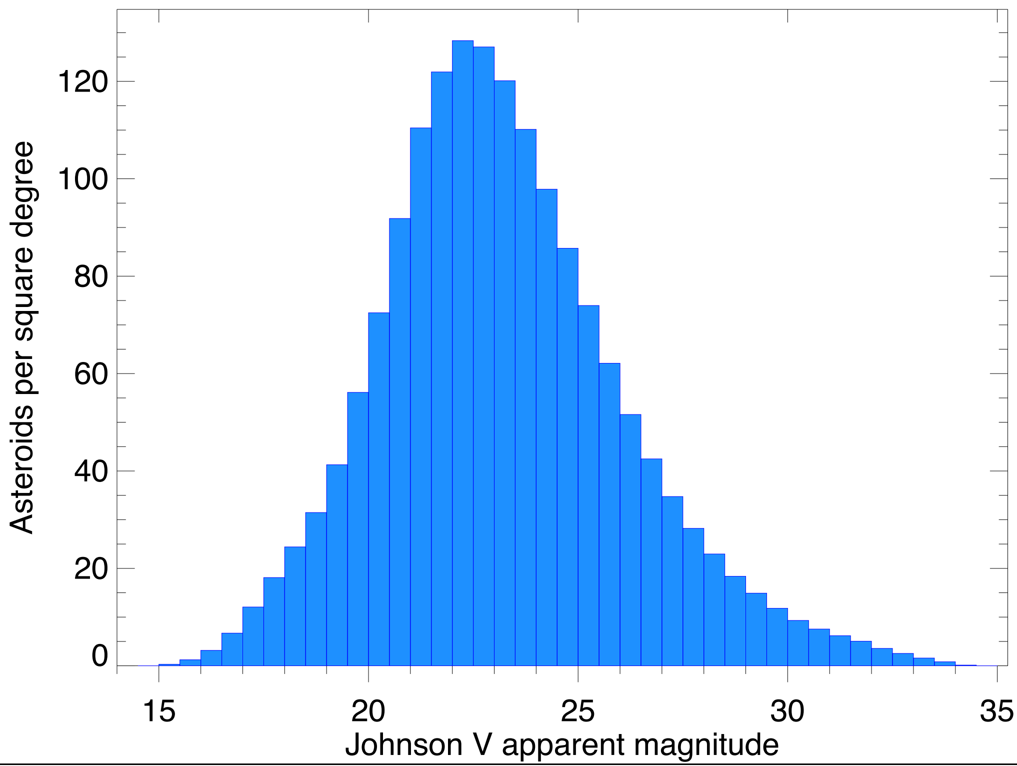

Figure 1: Frequency of main belt asteroids (MBAs) between 10 m and 27 km in diameter per square degree as a function of apparent magnitude in the Johnson V filter. The peak frequency is between 22.0 and 22.5 mags. These results are representative of the entire population of minor bodies in the solar system, not just MBAs, due to the much smaller number of other (detectable) minor bodies and the observation bias towards larger targets at larger heliocentric distances. Assuming a uniform distribution of objects, hundreds of minor bodies should be present in each square degree of sky near the plane of the ecliptic.

Targeted irregular satellite surveys

The irregular satellites of the giant planets are a diverse collection of minor bodies thought to have been captured early in the history of the solar system. While almost all irregular satellites are thought to be the result of capture, the source populations are still debated. They may have originated from extant or primordial minor body populations, but their exact origins remain uncertain due largely to the small number currently known (~100). Further frustrating efforts at determining irregular satellite origins are their wide range of orbital parameters and the lack of well-constrained physical characteristics (e.g., size and albedo) and surface compositions. At this point in time, *in situ* spacecraft observations actually provide our best views of irregular satellites, but to-date only two have been visited: Saturn's moon Phoebe (Johnson and Lunine, 2005) and Neptune's moon Triton (Agnor and Hamilton, 2006). Both objects appear to have their origins in the Kuiper Belt, but it is also clear from these limited observations that not all irregular satellites fit this paradigm, implying additional source populations.

In an effort to better understand their origins, the irregular satellite populations of Jupiter and Saturn were categorized into "families" based on their orbital properties (inclination, eccentricity, semi-major axis, direction of orbital motion). Common origins, either from the same source population or through collisional processes, were identified for irregular satellite families through this process (Gladman et al., 2001; Nesvorný et al., 2003; Sheppard and Jewitt, 2003; Jewitt and Haghighipour, 2007; Holt et al., 2018). Probing the Hill spheres of the giant planets (the volume of space where that planet's gravity dominates over the Sun's and satellites can have stable orbits) for additional small, faint irregular satellites would move the inventories of these populations closer to completion and help to further inform origin theories.

Assuming next-generation space-based facilities can reach a limiting magnitude of V~28 in a reasonable exposure time, irregular satellites down to approximately 0.3, 1.0, 4.5, and 11.4 km in diameter could be detected around Jupiter, Saturn, Uranus, and Neptune, respectively. We used these diameter limits in combination with an estimated size distribution supported by observations (Nicholson et al., 2008; Bottke et al., 2010) to estimate the number of irregular satellites that we would expect to detect with such a space telescope. With no preference for irregular satellites on prograde or retrograde orbits, and assuming only half of the unknown irregular satellites larger than the diameters estimated above are discovered, we would expect to identify approximately 1000, 200, 100, and 5 new irregular satellites around Jupiter, Saturn, Uranus, and Neptune, respectively. Compare these numbers to the 60, 40, 10, and 5 currently known irregular satellites around each of the giant planets. The increase in the number of detected objects is because current surveys are unable to detect the more numerous collisionally produced irregular satellites, which are smaller and fainter.

The search efficiency for new irregular satellites would benefit significantly from a space telescope with a large field of view. The search regions of interest around the giant planets correspond to the angular extent of each planet's Hill sphere; the solid angle of the giant planets' Hill spheres as seen from Earth are 4.7, 3.0, 1.5, and 1.5 deg^2, respectively (Sheppard, 2006). However, dynamical stability studies by Hamilton and Krivov (1997) find that satellites are not truly stable over the entire volume of the Hill sphere; the maximum semi-major axis for an irregular satellite on a retrograde orbit is only ~67% of the Hill radius. This fraction is even smaller for an object in a prograde orbit. Table 1 presents the size of this "stability region", as well as the semi-major axis of the furthest currently known irregular satellite around each giant planet. Even given this stability constraint, a very large fraction of the stable volume of each giant planet's Hill sphere remains to be searched; this region also covers larger angular distances from the primary, so scattered light from the giant planet is negligible. This is not surprising given the small field of view of the ground-based telescopes typically used to carry out these surveys and the difficulty in obtaining the observing time necessary to image the entirety of the Hill spheres to an appropriate depth for detection of the smallest irregular satellites.

A space-based facility with deep imaging capabilities and a FOV between 0.2-0.5 deg^2 would revolutionize the study of irregular satellites and their origins. Jupiter's Hill sphere has the largest angular extent on the sky and the field of view of WFIRST (0.28 deg^2), for example, could cover the entire area in only 17 pointings, compared to the nearly 2000 pointings for an imager with a field of view 3 arcminutes on a side. What is currently a prohibitively long survey could be undertaken in only a few hours.

Table 1. Giant planet Hill spheres

Planet	Hill radius (10^7 km)	Stability region (10^7 km)	Semi-major axis of furthest known satellite (10^7 km)	% vol. of Hill sphere known to be occupied
Jupiter	5.32	3.56	2.86	52
Saturn	6.53	4.38	2.45	18
Uranus	7.00	4.69	2.09	9
Neptune	11.6	7.77	4.93	26

A survey to detect Inner Oort Cloud objects

Minor bodies at the edge of the solar system are time capsules that preserve the history of the formation of the solar system, and the distribution of their orbits may provide clues to the existence of a potential, distant giant planet (Batygin and Brown, 2016). These distant minor bodies, including those in the "Inner Oort Cloud" ($r \gtrsim 100$ AU; Hills, 1981) and the Oort Cloud proper, provide valuable compositional information on the original solar nebula but, typically, observers must wait until they make the extraordinarily long journey into the inner solar system in order to detect and study them. The size of this population is very poorly constrained but must be known to better understand the formation and dynamical evolution of the early solar system.

At the time of writing, only one object has been confirmed at heliocentric distances of 100 AU or greater: 2018 VG_{18}, at ~125 AU (Sheppard et al., 2018). A handful of other objects have been identified with orbits that result in them spending significant periods of time beyond 100 AU, but none of these detections were made when the objects were beyond 100 AU (Brown et al., 2004; Trujillo and Sheppard, 2014; Trujillo et al., 2018). This is due to the extremely large distances involved, as well as the physical characteristics of the objects themselves: Small sizes and surfaces darker than asphalt (albedos <5%) combine to produce very low reflected fluxes (Fig. 2). Thus, space-based observations using instruments with high sensitivities and large quantities of observing time are necessary to attempt to detect small bodies in the Inner Oort Cloud.

Very long exposures of 1000s of seconds or more are required to detect distant, faint Inner Oort Cloud objects, but there is a practical limit for exposure length set by cosmic rays. According to Robberto (2010), the flux of cosmic rays at the Sun-Earth L2 point is ~3.3 per square centimeter per second averaged over a full solar cycle, assuming a shielded focal plane. Adopting the WFIRST Wide Field Imager (WFI) parameters for pixel area (100 μm^2) and physical detector area (~300 cm^2), and assuming only one pixel is affected by each cosmic ray strike, ~0.33% of pixels would be affected in a 1000-second exposure and ~3.3% would be affected in a 10,000-second exposure. However, it is more realistic to assume that the pixel hit by the cosmic ray and each adjacent pixel would be affected, meaning that ~1.65% and ~16.5% of pixels would be affected in a 1000-second and 10,000-second exposure, respectively.

Given this information, we now outline a hypothetical survey with the dual goals of identifying Inner Oort Cloud objects and surveying faint astrophysical sources that may not be detected as part of other astrophysics surveys, such as very high-redshift galaxies. The survey strategy is to obtain ten 1000-second exposures at one pointing, then return at a later time (<1 day) and obtain ten 1000-second exposures of a second field offset from the first. Overlapping the two fields by ~25% provides deeper imaging over a reasonable amount of the first field while still increasing the total survey area. This process would be continued over days to years in order to build up a large, deep survey region. Compared to the isotropic distribution of comets in the Oort Cloud (Dones et al., 2004), the shape of the Inner Oort Cloud is possibly more disk-like, centered on the ecliptic, with a larger spread in ecliptic latitude as heliocentric distance increases. This results in a higher density of objects over a smaller area of sky, increasing the chances of Inner Oort Cloud object(s) present in any particular pointing. An ideal region for the survey would be a few tens of degrees above or below the ecliptic plane, outside regions heavily populated with low-redshift galaxies, and off the galactic plane in order to avoid source confusion.

An object at the lower end of the range (100 AU) will move ~4 pixels (at ~0.1" per pixel) over a 10,000-second period and ~32 pixels over the course of one day, whereas objects at 600 AU will only move ~2 pixels over the course of one day. Re-imaging quadrants of earlier fields over the span of a few days would therefore allow for detection of objects over a large range of heliocentric distances. Use of a large field of view would increase the survey area at a faster rate compared to many currently operating ground- or space-based telescopes and would open a whole new frontier in the study of our solar system.

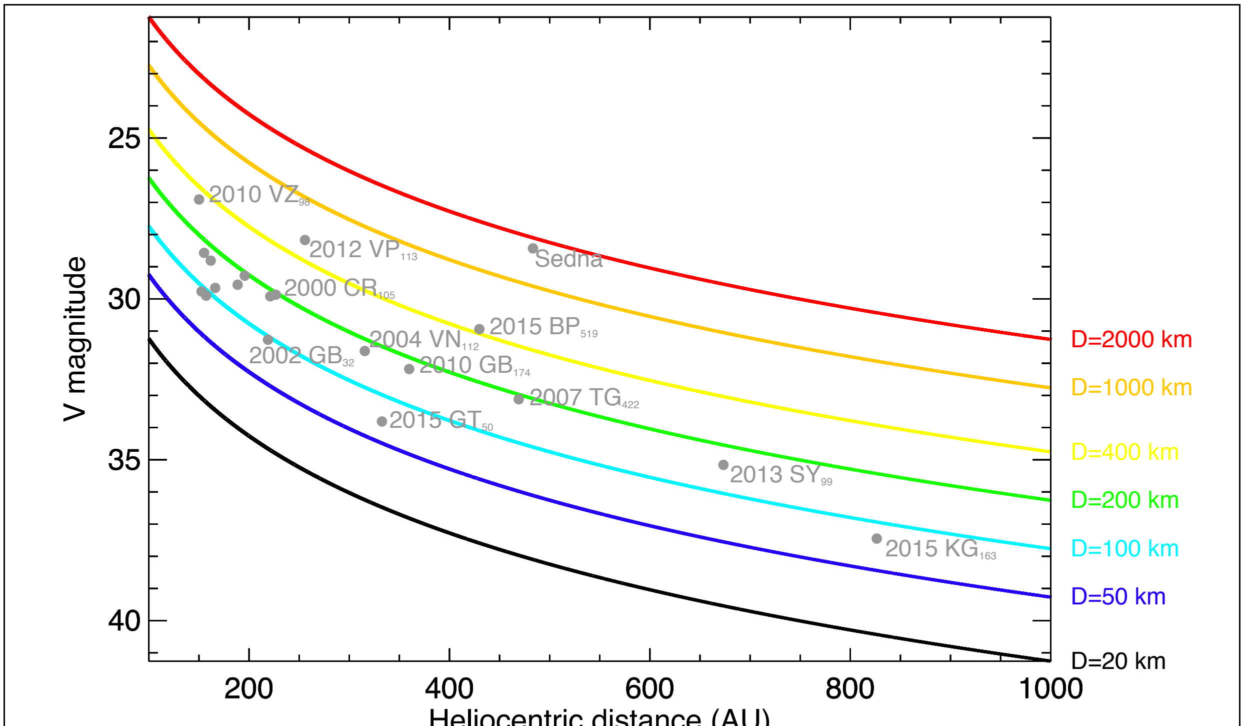

Figure 2: Johnson V magnitude as a function of heliocentric distance for hypothetical Inner Oort Cloud objects of different diameters (colored curves). The visible geometric albedo of these objects is assumed to be 0.10 (except Sedna, which has a measured albedo of 0.32). The grey points are known extreme KBOs (*q*>30 AU and *a*>150 AU); magnitudes were calculated for a distance equal to the semi-major axis of each object's orbit. (Adapted from Holler et al., 2018)

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